LINEAR PROGRAMMING APPLICATIONS FOR WOOD PROCUREMENT SYSTEMS

Matthew Reynders, University of Central Arkansas, 2435 Krystal Kreek Dr Conway, AR 72032
(920) 680 – 0240, mreynders1@cub.uca.edu

Mark E. McMurtrey*, Professor of MIS, MBA Director, College of Business 102-H, University of Central Arkansas, 201 Donaghey Ave., Conway, AR 72035-0001, (501) 450-5308, markmc@uca.edu

*****Corresponding Author

ABSTRACT

Linear programming is a mathematical tool that distributes limited resources among a variety of tasks in an optimal manner. The resources could be labor hours, machine hours, acres of land, or any other limited resource a company deploys in order to achieve an end result. Often the goal of managers using linear programming is to maximize profits or minimize operational costs. Linear programming's applicability is wide and practiced frequently in a variety of industries. One of the less frequently discussed industries, the forest products industry, also relies heavily on linear programming to aid in decision-making. Dutrow and Gransckog (1973) documented a pioneer sawmill manager who used linear programming to increase revenue by 45% and capacity by 36%. Due to the great variety of ways in which wood can be processed, this paper will not look into linear programming's applications for mill management. The focus of this paper will be linear programming's influence on the operational processes needed for the procurement of timber from the woods to the mill.

GROUND LEVEL – SELECTING IDEAL LOGGING EQUIPMENT

The supply chain in forest management begins with the timber harvest. The locations of these timber harvest sites all vary in their distance from the mill(s), the status of the road network connecting the site to the mill(s), the type of timber located on site, terrain, weather conditions, and the type of equipment needed to carry out the operation. This section will examine a method of mixed-integer linear programming (MILP) that minimizes the costs associated with the aforementioned components as well as determining appropriate logging equipment for a given site. MILP is a form of linear programming that restricts the resources of interest to whole numbers. For instance, if a firm is deciding on the number of logging companies to use to harvest units of timber, a solution with a fractional number of logging companies would not be practical.

Epstein el al. (2006) discussed an application of MILP that finds a solution for minimizing the costs of ground-level operations, particularly machinery location and road design (MLRD). Their method considers the type of machinery to use, essential road construction, transport and harvest costs, exit points, and economic variables that restrict harvests. The objective function was to minimize road construction, harvesting and transportation costs.

This MILP method starts tracking a logging operation when a tree is felled. There are a variety of methods to transporting felled timber to log site landings (location where log trucks are loaded with timber). The selection of the type of skidding (dragging) equipment is dependent upon site conditions. Topography, weather conditions and incidents, soil structure and composition, the volume of timber to be extracted and the distances to the landing sites will all vary from site to site (Epstein et al. 2006).

Tractors commonly skid felled timber to landing sites. Skidding tractors normally have rubber tires and a large grapple on their backside which grabs the logs. In areas where the topography or wet logging conditions preclude the use of tractor skidders, aerial methods are preferred. Use of aerial skidding methods require the installation of towers that are approximately 30 feet tall. Each tower contains two cables of varying lengths that are used to drag felled timber (Epstein et al. 2006).

Each method of skidding has certain tradeoffs. The tractor skidding method requires a more extensive road network to minimize the skidding distance. Aerial methods require far less extensive road networks as they cover larger areas. However, establishing an aerial system is substantially more expensive. Certain factors such as skidding distance, current road network, terrain, and other site conditions must be taken into consideration when selecting a skidding method. This selection process is critical when considering roughly 55% of total production costs come from timber harvest and road construction preparation (Epstein et al. 2006).

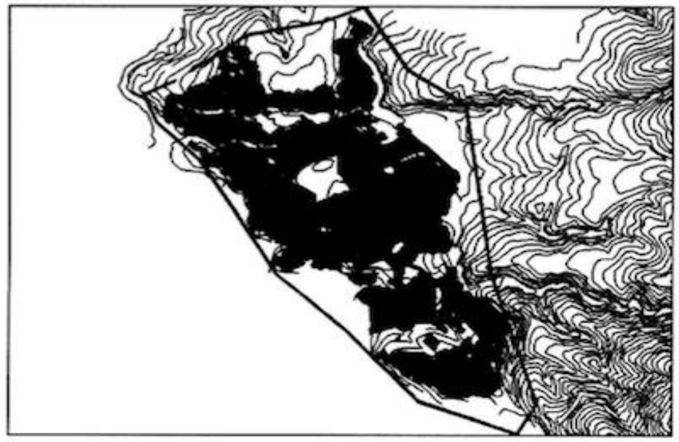

Figure 1. Graphical display of optimal mix of skidding methods. Darker areas represent areas where ground skidding is preferable and lighter areas represent where aerial methods are preferred. Thick lines indicate areas where roads should be constructed. Dark spots within lighter areas indicate tower location.

The results from the study graphically displayed the areas best suited for both types of skidding methods (Figure 1) (Epstein et al. 2006). Additionally, their results indicated which road networks should be utilized and which should be expanded upon.

Another study examined the appropriate mix of uphill skidding, downhill skidding and helicopter logging to implement on a 1,000-acre timber harvest unit in the Swiss Alps. Bont, Heinimann and Church (2015) used a methodology similar to Epstein et al (2006) by using MILP to minimize layout costs. Their model incorporates the cost of each skidding method, terrain restrictions for each (which indicates where helicopter logging is pref5
erable) and the existing road networks.

Firms using this methodology have reported a 15-20% reduction in operational costs. Benefits like this are not only realized by the firm, but also by the contracted or employed logging force. A collaborative approach between firm and logger can drastically improve morale as well as performance in the field (Epstein et al. 2006).

Another benefit to MILP methods discussed above is enhanced planning. Rather than relying strictly on foresters, management or forest technicians, this approach can take all variables into consideration. Manual planning is subject to human error and therefore, overlooks certain components to the planning process. Analysis and computation of the multitude of variables that go into operational timber harvest planning is taken out of the hands of the forest decision maker and is transformed into a tool that the decision maker has at their disposal (Epstein et al. 2006).

GROUND LEVEL - CUT-TO-LENGTH DEMAND INFLUENCE ON HARVESTING

Local fiber demand plays a big role in selecting timber harvest locations. It also influences the way in which logging equipment processes timber in the woods. Mill specifications, especially for sawmills, vary from location to location. Versatile procurement firms and logging companies tailor their operations to help supply a variety of mills with varying log specifications. This versatility is a strategic decision to avoid becoming too reliant upon one mill in particular. However, this decision to be versatile comes at a cost (Dems, Rousseau & Frayert 2013).

As opposed to the more conventional tree-length harvesting method, the cut-to-length method puts some of the production onus on the logger. The logger is required to cut the stem into segments out in the woods in preparation for further processing at a sawmill. This added step increases the operating costs for the logging contractor or for the firm employing the logging company. Tree-length harvesting is common for pulping and paper mills because the timber will ultimately be chipped and not sawed. A logger may have to keep note of several different sawmill specifications if he or she operates in an area with multiple sawmills (Dems, Rousseau & Frayert 2013).

The complexity of this issue is magnified by the differing demands and prices for varying cut-to-length products. Dems, Rousseau and Frayert (2013) utilize MILP to develop a module that helps navigate this dilemma. Their methodology is applied to 30 heterogeneous tracts of timber spanning over 9,000 acres.

Dems et al. (2013) developed an objective function that maximizes the profit for operations for an entire year that take into account the revenue from each harvest, the cost of logging and a bucking incentive factor. The bucking incentive factor considers the estimated volume within a given tract and prioritizes a particular bucking method that is most efficient for the given quantity of logs on site. In other words, if there are more large diameter trees within a block of land, then the module matches these larger specifications with bucking methods preferable for larger diameter trees.

Constraints, in linear programming, are applied to the variables of interest to prevent unrealistic outcomes. For example, a common constraint in a linear programming problem is to limit the amount of labor hours per week to accurately account for labor restrictions. The methodology discussed previously contained 11 constraint functions that were applied to the aforementioned study area. Constraints 1 and 2 account for the number of different log types harvested in each cut block. Constraint 3 requires one bucking pattern per species per block. Constraint 4 limits the volume harvested for each species within a given block. Constraint 5 assigns a minimum and maximum demand quantity each product and species within a block must fall within. Constraints 6-9 place a penalty on products that are hauled off of smaller tracts. Logging firms require high volumes to offset transportation costs; therefore lower-volume tracts are more cost-prohibitive. Constraint 10 assures the variables are binary and constraint 11 assures non-negativity (Dems et al. 2013).

When applied to the 30 heterogeneous tracts of timber, the module found 28,259 constraints with 94,711 variables. The species of timber included white birch, black spruce, poplar, jack pine and balsam fir. Each block contained up to 25 log lengths (five species and five respective log lengths for each species).

The results showed an increase in profit maximization over existing methods to MILP. Existing methods assign a priority list per species to every cut block in the area of investigation. The method Dems et al. (2013) developed builds off of this approach by allowing different priority lists to be assigned to each cut block. This method more accurately links the timber type located on each site with mill demand. The computational time was approximately six hours for their method as opposed to 85 seconds for the common method. The bucking priorities for each block of land dramatically increased the amount of computational time required for analysis.

Forest companies that utilize the methods Dem et al (2013) present can benefit from a MILP module that accounts for many of the complexities most forest and logging firms are confronted with. As demand changes on a regular basis, this approach can help match inventoried data with anticipated demand as well as help plan harvests for the short term.

ACCESS LEVEL – APPROPRIATE LAYOUT OF HARVEST & ROAD ACTIVITIES

As stated previously, 55% of operational costs come from harvest and road activities. Current practices generally rely on an experienced individual or team of individuals that make harvest layout and road construction decisions based on experience and gut-instinct. Like the previous links in the supply chain, decision-making concerning road construction and layout can be greatly improved through MILP. Road design and layout encompass factors such as road composition (dirt, gravel, asphalt, etc.), volume of timber to be hauled on road network, road construction and maintenance costs, decisions when to upgrade current or create new roads, and connectivity to mill(s).

Bont et al (2015) used MILP to find the mathematical optima for minimizing the cost for the problem of laying out truck roads and cable roads when terrain is steep. The test area was a 1,000-acre block located in the central slopes of the Swiss Alps. The community of Evolene was considering building a road to access this harvest unit. The parameters of the study included the costs for the net present value of construction, maintenance, as well as off-road transport, like helicopter logging and downhill and uphill skidding.

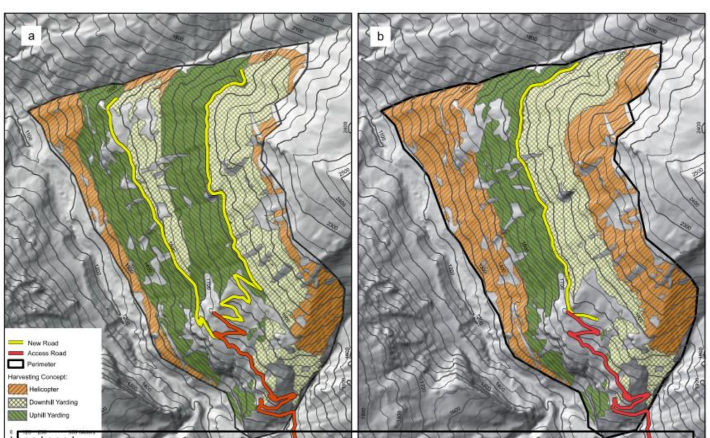

Figure 2. Comparison between methodology used by Andalaft et al. (2003) (A) and a previous study (B). Option A generated 7% more in savings than option B.

The area is logged primarily via cable-skidding in situations where access is not restricted. Helicopter logging is used when access is poor and the cost of access is not offset by the cable skidding. According to Bigbsy and Ling (2013) the use of helicopter logging minimizes soil disturbance and other environmental impacts, but is significantly more cost-intensive than aerial or tractor skidding. That extra cost, however, may be more cost-effective than establishing a new road network that will provide access for the cable-skidding setup.

The study's objective function was tailored to minimize costs for road constructions and harvesting activities. Some of the constraints assured that timber from each parcel was harvested either via cable-skidding or hffelicopter. If the parcel was harvested via cable-skidding, then the constraint required the construction of at least one road segment to provide access for the cable-skidding operation. Other constraints assured road connectivity and non-negativity (Bont et al 2015).

One component the study did not consider was the appropriate mix of gravel and dirt roads. Gravel roads are more expensive to install, but have lower operational costs and can be in use year-round. Dirt rounds are inexpensive to install, but are affected negatively by adverse weather conditions and therefore are more cost-intensive to maintain/cannot be used in wet conditions. Andalaft, Andalaft, Guignard, Magendzo et al (2003) considered this factor in their research regarding a Chilean private forestry firm. Their study looked into the availability of the existing road network and the potential to upgrade existing roads from dirt to gravel. Consideration of road composition is critical, especially in steep areas, where erosion is high.

Figure 2 geographically displays the optimal mix of activities found by Bont et al (2015). Critical to the efficacy of this study was the involvement of geographical information. Geographical data is oftentimes the limiting factor for various silvicultural practices. used here. Each cell in the raster grid contains information regarding the volume of timber to be harvested, the geotechnical classification of the subsoil, obstacles to cable-skidding, and a stream network. Existing roads were imported as vector data.

Dependent upon the parameters used, the computation took anywhere from four minutes to eight hours. This length of time for computation is insignificant when considering the importance of road and harvest layout decision-making. Attention to road composition and resting conditions should also be considered in this decision making. Unforeseen road construction or enhancement could add to operational costs. Forest managers can use MILP to appropriately weigh the complexities of road and harvest layout and get answers in a day's time (Bont et al. 2015).

TRANSPORTATION – OPTIMIZING WOOD HAULING TO WOOD MILLS

Once the operational layout as well as the selection of appropriate equipment are optimized, the next consideration should be minimizing the cost of transporting the product to the mill(s). Forested areas are diverse by nature. Mixed stands generate a great variety of products as a result of the species diversity. Even monocultures, like pine plantations, will yield both pulpwood and sawtimber. Unfortunately, paper mills, sawmills, and other common mills rarely exist in the same location. Thus, the distance away from the mill(s), the timber product type and quantity on site, and the coordination of multiple haul trucks are all significant components to efficient transportation management.

Hachemi, Hallaoui, Gendreau and Rousseau (2015) investigated this synchronized log-truck scheduling problem (SLTSP). Their objective was to minimize the overall transportation cost by taking into account pick-up and delivery requirements, the presence of multiple products on site, inventory levels at mills, lunch breaks, wait times at mills and hauling back from mills empty.

The study examined four cases. Cases 1 and 2 had six forest areas, five mood mills, and three timber products each. Case 1 averages 400 shipments per week with an average roundtrip time of 4 hours. Case 2 averages 700 shipments per week with an average roundtrip of 5.5 hours. Cases 3 had nine forest areas, an average of 560 shipments per week and an average roundtrip of 5.5 hours. Case 4 had eleven forest areas, 583 shipments per week and average roundtrip of 4 hours. Both cases 3 and 4 had seven wood mills and five timber products.

Hachemi et al. (2015) developed a flow-based model (Figure 3) and applied a branching strategy to minimize the wait-time component of the objective function to better synchronize activities. The clustering of the nodes displayed in Figure 3 represent the spatial restrictions of the SLTSP. The S node and resulting arc represent the log truck start point and travel to the forest area. The wood mill node to the E node represents the log trucks' travel from wood mill to end location. The wood mill node to the forest area represents the unloaded log trucks' travel (deadheading) from the wood mill to the forest area. The arc connecting two wood mill nodes represents the lunchbreak. Waiting time at the wood mill is represented by two wood mill nodes connected vertically. Log truck loading in the forest area is represented by two forest area nodes linked horizontally. Log truck unloading at the wood mill is represented by two wood mill nodes connected horizontally (Hachemi et al. 2015).

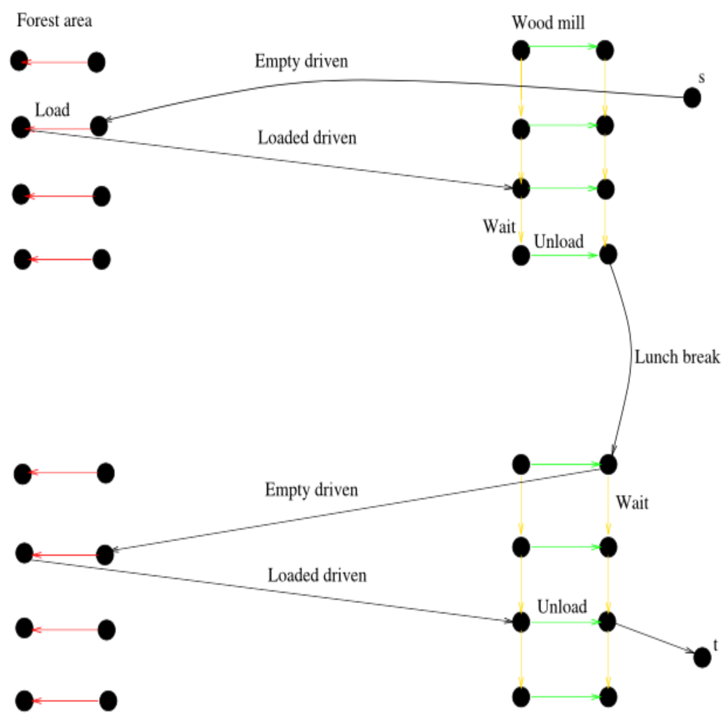

Figure 3. Flow-Based Model developed by Hachemi et al (2015)

The branching strategy mentioned previously considers the variable cost of log-loader wait-times. Log-loader wait-time costs are approximately double the hourly cost of log trucks. Minimizing log-loader wait-time prevents extended idling hours or the number of start and stops for the log-loader. Accounting for this component better synchronizes the forest activities with the transportation activities. The goal is to keep the log-loader in operation only when it is serving its purpose, loading log trucks (Hachemi et al. 2015).

The method Hachemi et al. (2015) developed showed a decrease in forest area and transportation activities costs for each case. Larger cases did not show reductions in cost as high as seen in the smaller cases. As the number of mills, forest areas and products increase, the SLTSP becomes much more complex and therefore, the reduction in costs using this methodology becomes smaller.

Finding methods to improve log-truck synchronization and to minimize the associated costs can dramatically lower operation costs. McDonald, Taylor, Rummer and Valenzuela (2001) determined that transportation of wood fiber can account for up to 50 percent of total harvest costs. Firms that improve log-truck synchronization can achieve a just-in-time inventory system which can eliminate excessive oversupply and minimize inventory costs (Hachemi et al 2015).

FOREST MANAGEMENT DECISIONS – CONSIDERATIONS TO HELP MANAGE PROCUREMENT SYSTEMS

Managing a Land-Base for Sustainable Use

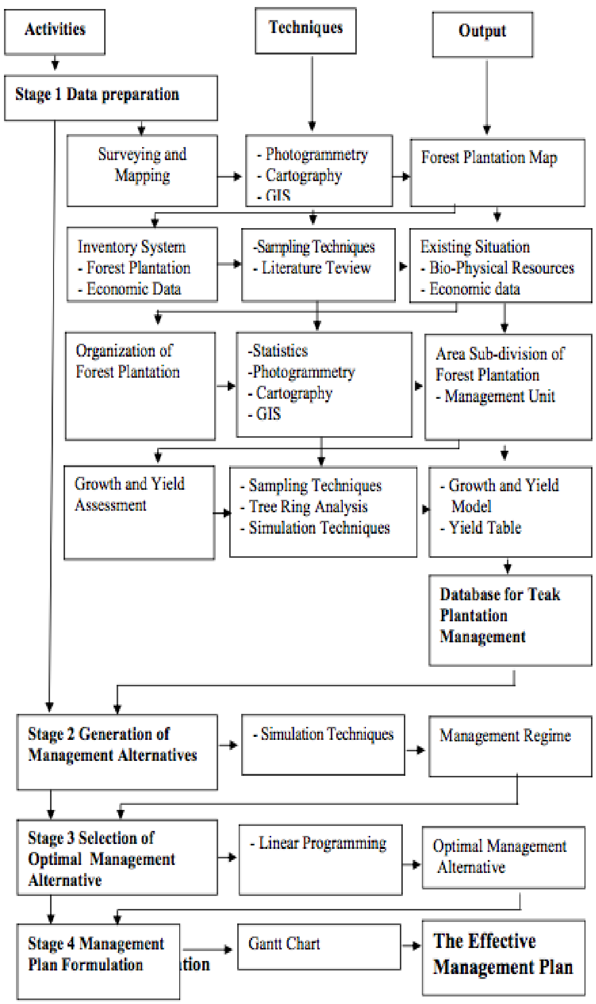

Figure 4. 4-step process developed by Duangsthaporn and Prasomsin (2005) to achieve alternative scenario analysis

The previous sections have provided examples of ways to utilize linear programming for ground-level operations. But what about the decision-making that initiates these activities? Foresters have to account for the sustainability of their operations relative to environmental regulations and the perpetuity of their firm's existence. Gunn (2009) explains "Strategic forest management analysis begins by defining the land base and the types of allowable silvicultural activities on this land base." Linear programming is commonly used in the forest products industry for determining the appropriate activities to implement in order to accomplish sustainability.

The predominant application of linear programming for forest management strategy is to identify the maximum net present value of all prescriptions and harvest flows over the life of a forest stand. A given stand, when reforested, will require site preparation costs, like the cost of planting, burning, release spraying and subsoiling. All these activities prepare the site for successful establishment of a plantation. Naturally regenerated stands may also generate site preparation costs in the form of activities that eliminate undesirable species. Most LP models have constraints regarding the forest growth and management strategies across the area of interest. The models also consider the sustainability of forest products as well as environmental requirements that maintain wildlife habitats, scenery and water quality. LP is not used directly for strategy, but rather as a mechanism that provides the consequences for certain management alternatives (Gunn 2009).

Many site variables must be accounted for when using LP to assist with strategy. The identification of riparian zones that must be protected, the percentage of land base that must meet old-growth forest requirements, and the percentage of land base that is dedicated for recreational purposes must be considered. LP can help weigh the costs associated with the intensity by which the aforementioned constraints are adhered to. The greatest benefits LP can bring to decision-making is its unambiguous calculations of feasibility or infeasibility for alternative situations and the ability to show how much constraints are costing a firm (Danzig 1963). ff

Gunn (2009) applied LP to a scenario comprising 1,000 stands of forested area over a 100-year period. Constraints applied were non-declining yield for both hardwood and softwood and establishing a minimum average age for the 1,000 stands at the end of the 100-year period. These constraints prevented depletion of the forested areas throughout the period. The results generated 9,698 variables and 1,085 constraints. Gunn (2009) used a 60-year rotation age for age for clear-cutting each stand. A discount rate of 3% was used and the resulting NPV was $23,059,629.45. The scenario achieved 99.5% of the objective.

The applicability of Gunn's (2009) study is easily realized. Nova Scotia's provincial geographical information system (GIS) contains up to 10,000,000 forest stands. The complexity of the LP model will greatly increase when other variables are considered. However, Gunn (2009) has outlined a method by which decision-makers can generate alternative outcomes for vast acreages of land. Duangsthaporn and Prasomsin (2005) conducted a similar study to Gunn (2009) and created a diagram that effectively displays the variables mentioned previously (Figure 4) LP has and will continue to lend itself as an effective medium for land-base analysis.

Using LP for Contingency Scenarios

All firms operating in the forest products industry are susceptible to natural disaster. These disasters can require immediate consideration of each phase of the wood procurement supply chain. Southern Sweden was hit with hurricane force winds by Storm Gudrun during the weekend of January 8-9 2005 (Figure 5). The resulting damage was estimated to be 70 million cubic meters of wind-felled timber. Applying the prevailing market prices at the time, the damage was 3.2 billion euros worth of downed timber. The disaster sent forest companies in the area into a tailspin. The questions that needed immediate answering were as follows: How much volume was wind-felled and where? Was the available harvesting capacity enough? Was the available transportation capacity enough? How to supply existing customers? Where to store excess wood? What are the immediate effects on the wood markets? Broman, Frisk and Ronnqvist (2009) developed a model using integer programming to assist a local firm, Sveaskog, in developing a logistics strategy.

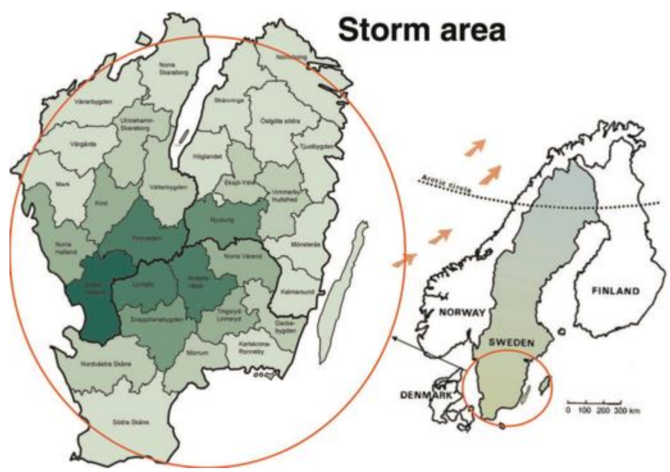

Figure 5. Area affected by Hurricane Gudrun

Sveaskog manages over 8.5 million acres of productive timberlands in Sweden. Storm Gudrun affected approximately 1.2 million acres of their land-base. The estimated volume was 2.5-3 million cubic meters of timber spanning several species and product types. Amidst the destruction caused by Gudrun, Sveaskog was facing a logistical nightmare. Coordinating logging harvests, determining appropriate transportation methods, fulfilling commitments with existing customers and aiding customers affected by the storm become the priority. Additionally, determining ways to store excess timber was an issue. Sveaskog also had to consider ground-level constraints. The sheer volume of felled timber required the use of heavy harvesters and forwarders. Due to the extent affected by the storm, chainsaw operations also had to be implemented. Chainsaw operations in wind-felled timber are extremely dangerous. Wind-felled timber often is under a great tension and is chaotically strewn about harvest units, creating hazards. Sveaskog also needed to determine locations where extra wood could be stored (Picture 1).

Broman et al (2009) developed a model that considered three decision criteria: the proportion of each harvest area and forest type to be harvested by a given machine type, which parts and proportion of the forests not to harvest, and which terminals excess supply should be stored. The constraints for their model were the limited transportation capacity, the limited harvesting capacity and the linking between supply and harvesting decisions.

Picture 1. Timber stored at airport Byholma. Estimated to be 800,000 cubic meters of timber

Sveaskog used the plan devised by Broman et al (2009) to navigate the crisis. Some of Sveaskog's implementation of the plan diverted from the plan on paper. For example, the model determined the optimal mix of large-medium-small units to be logged was 54-59-32, respectively. In reality, Sveaskog logged 64-74-14, respectively. However, the few deviations from the outlined plan do not belittle the impact the plan generated by integer programming had for Sveaskog. Critical decision-making was generated in under one minute. The solution helped Sveaskog prioritize which units to harvest, which harvest methods to use, which transportation methods to use and which terminals to store excess timber.

The utility of the integer programming model developed by Broman et al (2009) is to have prompt decision-making in times of crisis, when fast-acting implementation of activities throughout each phase of the supply chain is needed immediately. Forestry firms owning property should consider preemptively developing similar models to mitigate damage to their assets (standing timber) from natural disasters.

CONCLUDING REMARKS

Linear programming has and will continue to provide insight into the processes associated with wood procurement. Each phase creates complex problems that warrant consideration for a multitude of variables. Foresters achieve prompt solutions for these problems in a reasonable timeframe. Further research should investigate LP methods that link each phase of the procurement supply together. Currently, most LP methods are specific to a single phase, like log truck synchronization. LP solutions that integrate these phases could greatly benefit a firm, especially since LP solutions for a specific scenario could potentially conflict with a solution for another scenario. For example, if a certain harvest flow is ideal for paper mill demand, but not optimal for sustainability for the firm's land base, the LP solutions will only complicate the process. Finding a way to integrate these phases together could properly unite the entire supply chain for a wood procurement firm.

*References are available upon request.